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Work was performed under Research Contract No. 3004/RB
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"The cross-section data obtained from this experiment
are available under the accession number EXFOR-30668"

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ABSTRACT

Total neutron cross-section measurements have been performed for poly and mono-germanium crystals in the energy range from 2 meV - 1 eV. The measurements were performed using two TOF and a double axis crystal spectrometers installed at the ET-RR-1 reactor.

The obtained neutron cross-sections were analyzed using the single level Breit-Wigner formula. The coherent scattering amplitude was determined from the Bragg reflections observed in the total neutron cross-section of Ge and the analysis of its neutron diffraction pattern.

The in coherent and thermal diffuse scattering cross-sections of Ge were estimated from the analysis of the total cross-section data obtained for Ge mono-crystal. The following results have been obtained :

$\sigma_s = (9.24 \pm 0.09)$ b

$\sigma_{coh} = (8.5 \pm 0.1)$ b

$\sigma_{incoh} = 0.4$ b

$\sigma_{th.d.}$ (at 0.02 eV) $= 0.8$ b

$\sigma_{abs.}$ (at 0.0253 eV) $= (2.25 \pm 0.14)$b

The predicted resonance parameters of a bound level are:

$E_0 = -0.33$ keV , $\Gamma_\gamma = 0.16$ eV and $g\Gamma_n^0 = 0.22$ eV

1. INTRODUCTION

The germanium is one of the materials intensively used in manufacturing of the semiconductor detectors. The available total neutron cross-sections of Ge below 1 eV are those reported by Wu et al. [1], in the neutron energy range from 0.014-9.1 eV, and Fulfaro et al. [2], in the range from 0.0201-0.684 eV, using samples from germanium metal. These two sets of data are quite inconsistent; this is mainly due to the difference in the used samples. Accordingly, the determination of the total and partial neutron cross-sections of Ge, in the thermal neutron energy range, is worthwhile.

Single crystals have found wide application as thermal neutron band pass filters for fission reactors [3-6]. Brugger et al. [7] reported the results of their transmission measurements with a single silicon crystal. For such a purpose, they used a large single crystal (28 cm in length). In their work they prove that such a length is sufficient for removing neutrons of energies > 1 eV, where σ_t for Si crystal is ~ 2.25b. Recently, Harvey et al [8] has reported their transmission measurements with a Cu single crystal. Consequently, it is useful to study the transmission of a single Ge monocrystal in the thermal neutron energy range. This can help in studying the validity of using Ge as a neutron filter, which is more effective in removing the gamma radiation, accompanying neutrons from reactor than Cu and Si.

The present work deals with total neutron cross-section measurements carried out both for poly and mono-germanium crystals in the energy range from 1 eV-2 meV.

2. EXPERIMENTAL DETAILS

2.1 The Poly-Crystalline Ge Samples

The poly-crystalline Ge samples were prepared from fine spec pure Ge powder (99.999%). Two samples with thicknesses 2.2×10^{22} at/cm^2 and 1.6×10^{22} at/cm^2, were packed in aluminium containers with thin aluminium windows (0.1 mm thick); they are used for time-of-flight transmission measurements. For neutron diffraction measurements, the sample was packed in a vanadium cylindrical container (5 cm height and 1.5 cm in diameter).

2.2 The Ge Mono-Crystal Sample

The Ge mono-crystal sample was prepared from cylindrical single crystal (3 cm in diameter and 2.5 cm thick) cut along the (111) axis.

2.3 Poly-Crystalline Ge Neutron Diffraction Measurements

The neutron diffraction pattern of the poly-crystalline Ge sample was measured using the crystal diffractometer installed in front of one of the horizontal channels of the ET-RR-1 reactor and described in Ref. [9]. Monochromatic neutrons with wavelength $\lambda = 1.02$ Å, selected out of the reactor spectrum by diffraction from Zn single crystal cut along the (002) plane. The sample was enclosed in a vanadium cylindrical container (5 cm height and 1.5cm in diameter). The neutron diffraction pattern obtained for angles 2θ between 10°-60°, within 10' steps, at room temperature is represented in Fig. 1. Five well separated peaks were identified confirming the Ge crystal structure.

The integrated intensities for the observed reflections were calculated using the area method and than corrected for background and Lorentz factor. The coherent scattering amplitude of Ge was deduced by fitting the corrected integrated intensities using the reliability factor method. The minimum reliability factor R was found to be 5% for a coherent scattering amplitude value (8.22 ± 0.05) fm of Ge

2.4 Total Neutron Cross-Section Measurements

The total neutron cross-section measurements were performed using two TOF spectrometers installed in front of two of the ET-RR-1 reactor horizontal channels. Each of the two spectrometers is equipped with an automatic sample changer unit, with remote control, used during the experimental measurements to drive the sample in and out of the neutron beam. This allows to perform the transmission measurements, both with and without sample, in runs taken during small time intervals. This minimizes the effect due to fluctuations in the reactor power, saving ~ 20% of the measuring time. The spectrometers resolution at different intervals of the whole energy range, under connderation, could be varied from 3 μ sec/m to 20 μ sec/m. The spectrometers are described in Ref. [10-11] .

3. RESULTS AND DISCUSSION

Fig. 2 shows the dependence of the total neutron cross-section on both wavelength and neutron energy for Ge polycrystal sample (closed circles) as measured in the energy range from 1.8 meV-1 eV. The cross-section values reported by Wu et al [1], in the energy range from 13.9 meV-0.826eV, are also displayed in the same figure (open circles). It is noticeable that the present cross-sections are higher than those of Wu et al [1] . Such discrepancy may be due to the large mosaic crystals of the Ge sample used by Wu.

The total neutron cross-section of Ge in the energy range from 1.0-0.08 eV was fitted using the least square method and found to be :

$$\sigma_t = \left[(9.24 \pm 0.09) + (0.36 \pm 0.02)\ E^{-1/2}\right]\ b$$

Where E is in eV.

The value (9.24±0.09)b stands for the free atom scattering cross-section and is in reasonable agreement with the value 9 barns reported in Ref. [13] . The formula yields the value [2.25±0.14] b for the absorption neutron cross-section of Ge at 0.0253 eV. It is in good agreement with the value (2.3±0.2) b reported in Ref.[12].

The contribution of the known close and faraway resonances σ_r upon the cross-section have been calculated using the single level Breit-Wigner formula, where the required resonance parameters were taken from the BNL-325 [12]. A bound negative energy level with the parameters $g\Gamma_n^c = 0.22$ eV, E_o =-0.33 keV and $\Gamma_\gamma = 0.16$ eV. The value obtained for the potential scattering amplitude R' is 6.9 fm which is in the same as that reported in Ref. [12].

The observed behaviour of the Ge total neutron cross-section shows sharp cut-offs at neutron wavelengths corresponding to the double interplaner distance d of the Ge crystal structure. Since the sample used is in a fine powder form (the grain size is less then 10^{-4} cm), the extinsion effects could be neglected. Table 1 gives the cut-off values of $\Delta \sigma_{hkl}$ corresponding to the reflection of neutrons with wavelengths from the planes with Miller indices hkl, the multiplicity factor M_{hkl} and the inter planer distance d (Å). The coherent scattering amplitude of Ge is calculated for each hkl plane (last column of table 1) considering both the resolution and Debye-Waller factor. The average value of b_{coh} has been determined and found to be b_{coh} = (8.2±1.1) fm, which is in good agreement with the value (8.21±0.05) fm obtained from neutron diffraction and is also in reasonable agreement, within the statistical accuracy, with the value(8.1858±0.0036) fm given in the BNL-325 [12].

Table 1 : The Ge Bragg cut-offs

hkl	M_{hkl}	λ (Å)	d (Å)	$\Delta \sigma_{hkl}$, b	b_{coh}, fm
111	8	6.532	3.266	8.5±2.0	8.3±0.9
220	12	4.000	2.000	5.6±1.0	8.1±0.7
311	24	3.412	1.706	7.0±1.0	8.2±0.6
400	6	2.828	1.414	1.0±0.5	8.2±2.0
331	24	2.596	1.298	1.5±0.5	8.1±1.3

Fig. 3 shows the total neutron cross-section of Ge mono-crystal as measured in the energy range from 2 meV- 1 eV. Also in the same figure are displayed the values reported by Fulfaro [2], in the energy range from 20.1 meV-0.684 eV. These values, along with the values of Wu et al [1] displayed in Fig. 2, were taken from EXFOR 30231 (IAEA). The agreement between the data of Fulfaro and the present cross-sections is reasonable.

The dashed line (Fig.3) represents the contribution of the absorption cross-section of Ge obtained from the least square fitting of the data represented in Fig. 2. One can see that the scattering cross-section is only about 1.2 barn for the single crystal at 0.02 eV. The calculation of the thermal diffuse scattering cross-section of Ge at 0.02 eV , following the procedure described in Ref. [13] , yielded the value 0.8 b. Accordingly the incoherent scattering cross-section of Ge is about 0.4 barn. This estimated value is in agreement, with the statistical accuracy, with the value 0.2 barn reported in Ref. [13].

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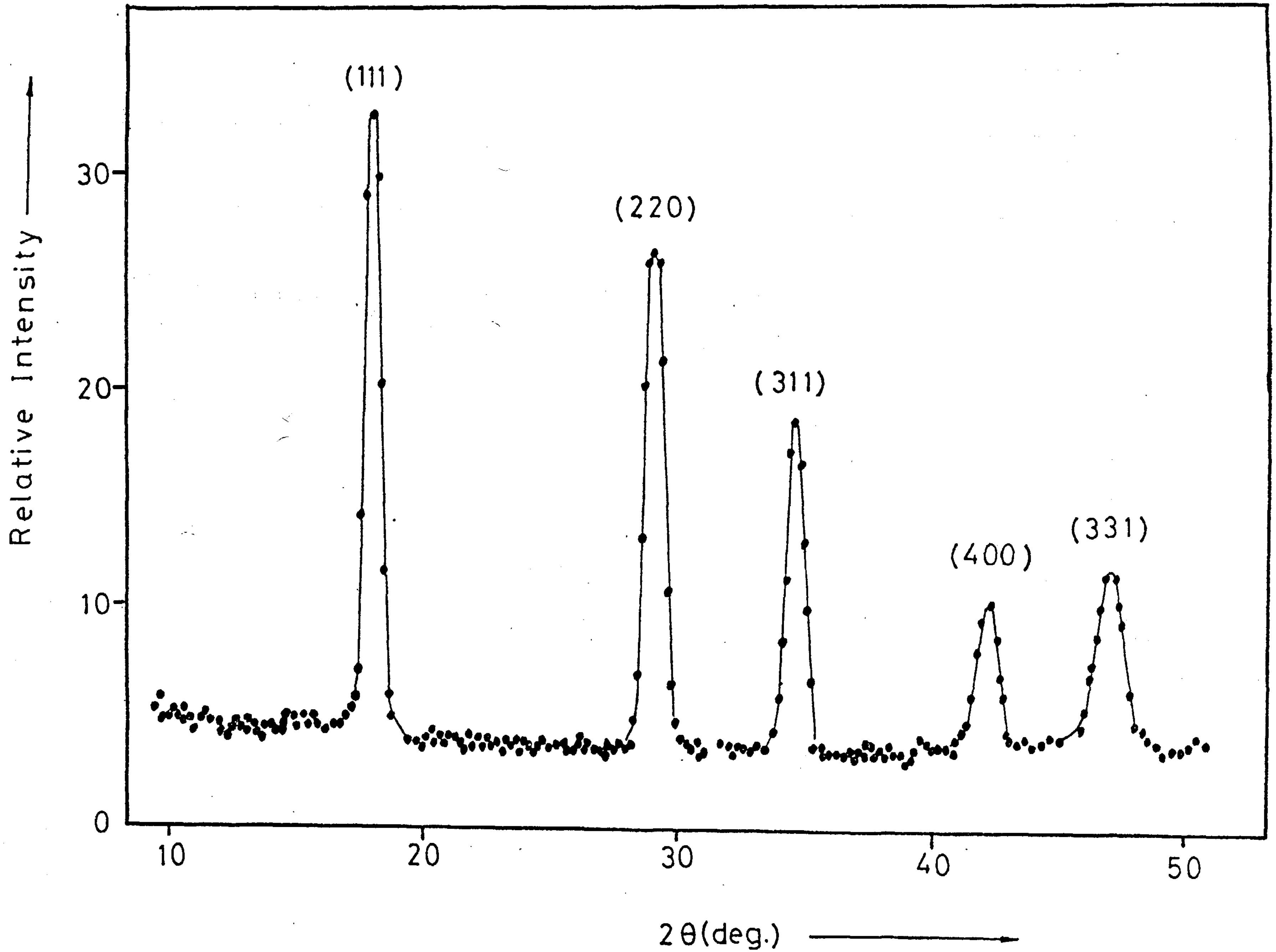
Figure Captions

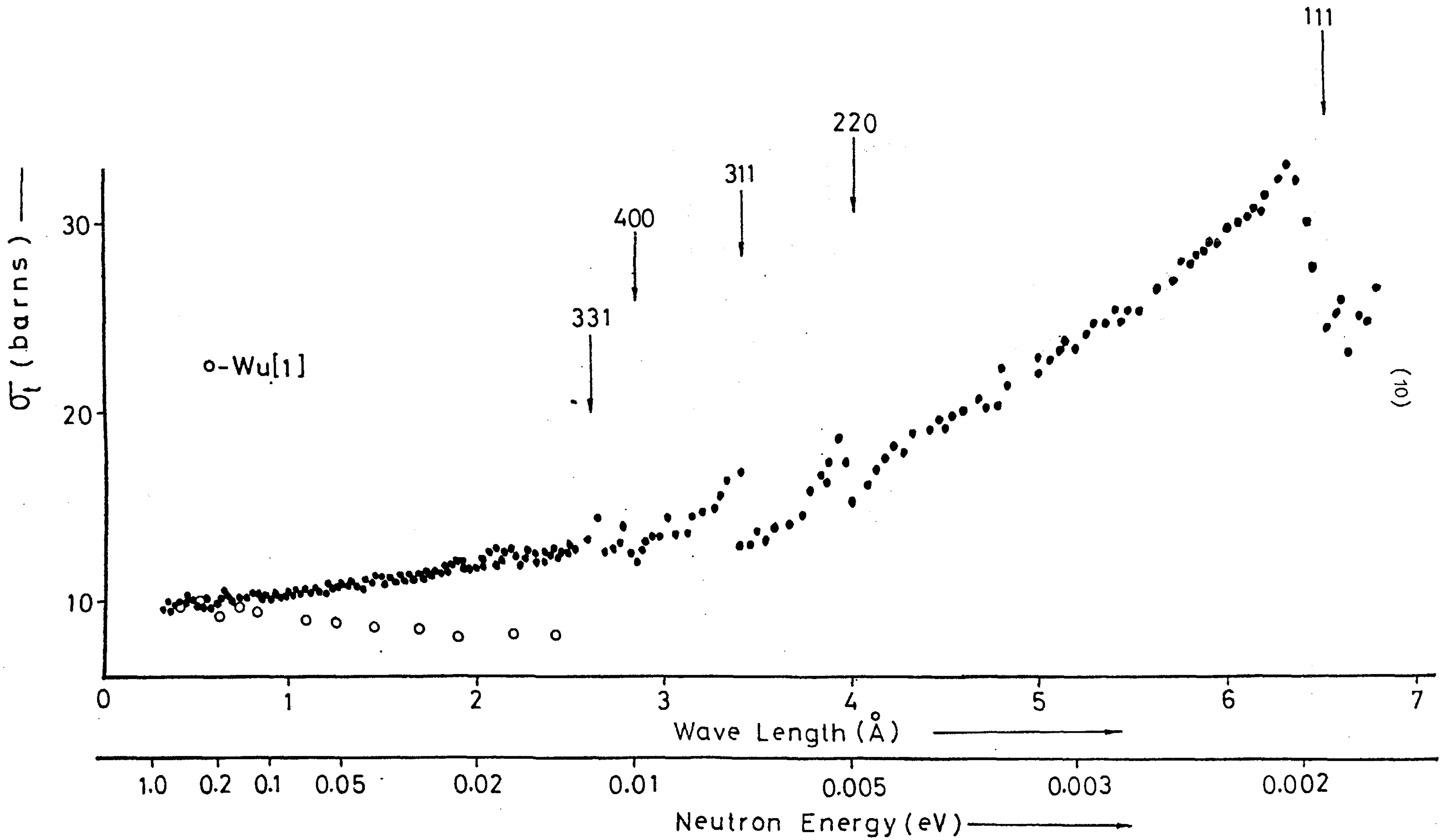
Fig. (1) : The neutron diffraction Pattern of Ge powder.

Fig. (2) : The total neutron cross-section of Ge poly-crystal.

Fig. (3) : The total neutron cross-section of Ge mono-crystal.


(111)
(220)
(311)
(400)
(331)
Relative Intensity
0
10
20
30
10
20
30
40
50
2θ(deg.)

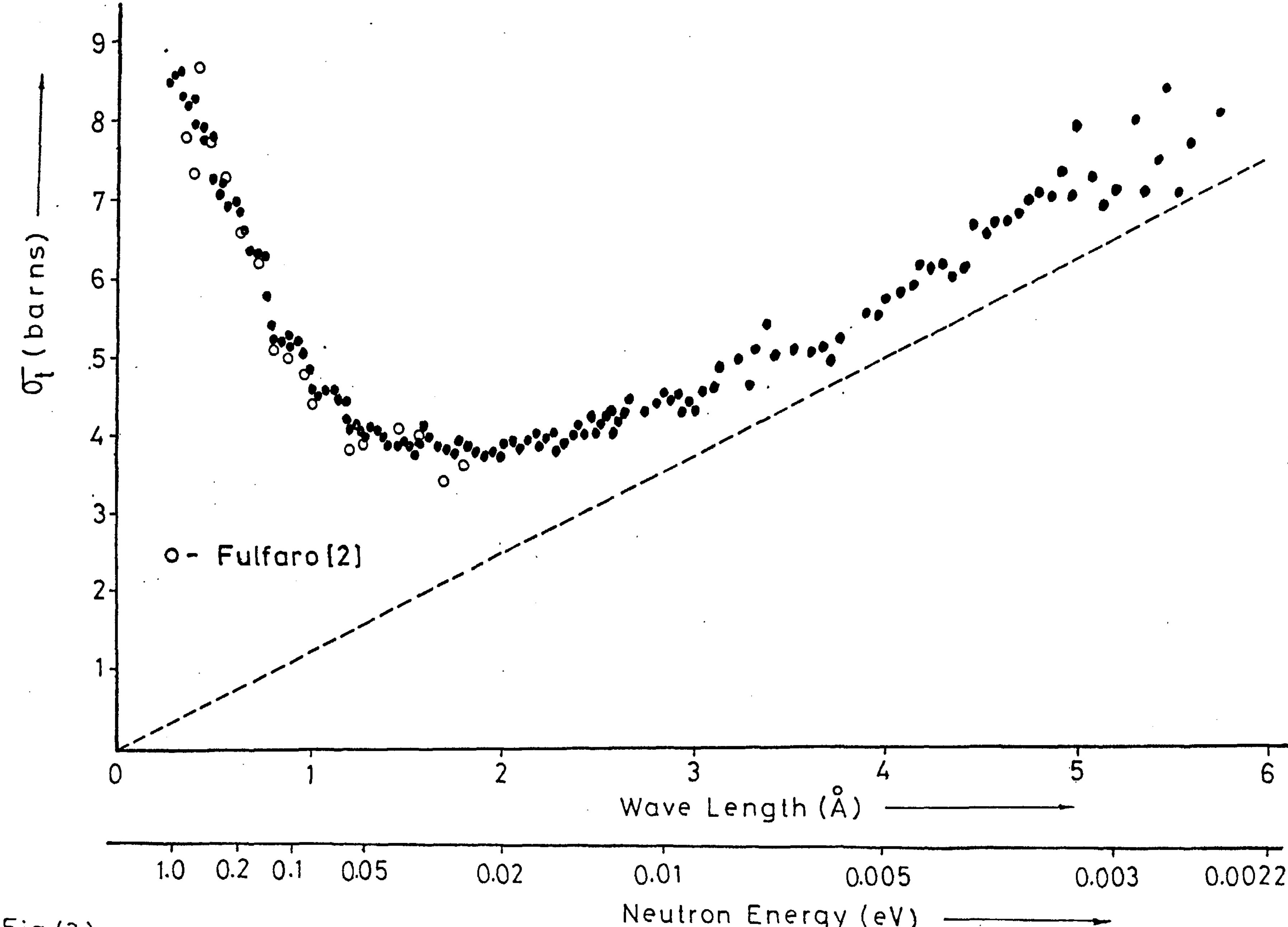
(6)



σ_t (barns)
30
20
10
o-Wu[1]
331
400
311
220
111
0
1
2
3
4
5
6
7
Wave Length (Å)
1.0
0.2
0.1
0.05
0.02
0.01
0.005
0.003
0.002
Neutron Energy (eV)

Fig.(2)

(10)



σ_t (barns)
9
8
7
6
5
4
3
2
1
o- Fulfaro [2]
0
1
2
3
4
5
6
Wave Length (Å)
1.0
0.2
0.1
0.05
0.02
0.01
0.005
0.003
0.0022
Neutron Energy (eV)

Fig.(3)